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# Energy production from biogas: A conceptual review for use in Nigeria

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ABSTRACT

The authors reviewed the global methods of biogas production, enrichment, compression and storage for energy generation and highlighted its potential application in meeting energy needs in developing countries, with emphasis on Nigeria. Biogas is becoming an increasingly important source of clean energy for rural and urban areas in developing countries, as can be seen by the increased construction of biodigesters. Biogas digester technology has been domesticated in Nigeria and a number of pilot biogas plants have been built with majority (over 75%) of operational Nigerian manure digesters on piggery, cattle farms or abattoirs. A trend is now seen among academic institutions in Nigeria in the design and construction of biogas digesters, for instance, the Usman Danfodio University Biogas Plant, the Obafemi Awolowo University plant, the University of Ibadan prototype (with a patent), Non-Governmental Organisations (NGOs) and Private sector involvement, which shows increasing interest and availability of biogas technology. Biogas is a renewable fuel that is 60–70% methane and can be used to power household appliances and generate electricity using appropriate technologies. These technologies include Biogas digesters which are being used to collect farm animal waste and convert it to biogas through anaerobic bacterial processes. The biogas generated is enriched through a process of scrubbing to obtain at least 95% purity. The current research focus of the authors towards improving biogas yield, enrichment, compression and storage for use in Nigeria is discussed. The current findings indicate that there are economic advantages for the utilisation of biogas in developing countries like Nigeria.


**Contents**



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## 1. Introduction

Biogas is the name of the mixture of carbon dioxide, $CO_2$ and inflammable gas Methane, $CH_4$ which is produced by bacterial conversion of organic matter under anaerobic (oxygen-free) conditions [18]. It originates from Methanogens (methane producing bacteria) in the process of bio-degradation of organic material under anaerobic (without air) conditions. Biogas is a source of renewable energy. It has the advantages of being an eco-friendly source of energy in that the calorific value of biogas is equal to that of half litre of diesel oil (6 kWh/m$^3$). Biogas is fully capable of replacing other rural energy sources like wood, hard coal, kerosene, plant residues, and propane. Hard coal possesses a calorific value of 8.5 kWh/kg per 0.7 kg. In a developing country like Nigeria where more than 60% of the rural dwellers rely on wood and hard coal for energy, over 50 million metric tonnes of fuel wood is consumed annually, a rate, which exceeds the replenishment rate through various afforestation programmes [19]. Local capability exists in Nigeria for building both floating dome and fixed dome biodigesters using a variety of bio-resources. Biogas digester technology has been domesticated in Nigeria and a number of pilot biogas plants have been built with majority (over 75%) of operational Nigerian manure digesters on piggery, cattle farms [19] or abattoirs [1]. A trend is now seen among academic institutions in Nigeria in the design and construction of biogas digesters, for instance, the Usman Danfodio University Biogas Plant, the Obafemi Awolowo University plant [2], the University of Ibadan prototype (with a patent) [24], Non-Governmental Organisations (NGOs) and Private sector involvement [1], which shows increasing interest and availability of biogas technology. Increasing interest in producing renewable energy has led to a renewed interest in the anaerobic digestion of manure [1] and Nigeria has the capacity of producing an estimate of 15.319 milion tonnes of agro waste and municipal solid waste which can be used for generating biogas [16,19]. However, biogas has not been commercialised in Nigeria, most of the biogas plants are situated on farms and are used as it is produced, mainly for cooking. The main problems associated with the commercialisation of biogas are:

- Its low energy content per unit volume.
- It is difficult to liquefy.
- Small scale production of biogas.

For the commercialisation of the biogas, it is important to make it portable and compatible for various commercial purposes. For that, the energy content for a particular volume must also be increased. This requires the compression of the gas to as higher pressures as possible [3]. For a successful commercialisation of biogas in Nigeria, it is necessary to increase its energy content through the purification of the gas to remove the incombustible gases and compress it in order to make it portable.

## 2. Biogas digesters

For the production of biogas, organic material, such as animal and plant waste is placed along with water into an oxygen free tank, or in some cases plastic membrane for digestion which is known as the digester. The organic matter is fed into the vessel and the resulting gas is outlet through a pipe that inlets above the waste liquid levels in the tank. Similar mechanisms are achieved using plastic membranes, which are contained in secure enclosures in the ground. Various digester designs exist.

### *2.1. Types of biogas plants*

The three main types of simple biogas plants are:

balloon plants,
fixed-dome plants, and
floating-drum plants [14].

#### *2.1.1. Balloon plants*

The balloon plant consists of a digester bag (e.g. PVC) in the upper part of which the gas is stored. The inlet and outlet are attached directly to the plastic skin of the balloon. The desired gas pressure is attained through the elasticity of the balloon and by added weights placed on it.

#### *2.1.2. Fixed-dome plants*

The fixed-dome plant consists of a digester with a fixed, non-movable gas holder, which sits on top of the digester. When gas production starts, the slurry is displaced into the compensation tank. Gas pressure increases with the volume of gas stored and the height difference between the slurry level in the digester and the slurry level in the compensation tank.

#### *2.1.3. Floating-drum plants*

Floating-drum plants consist of an underground digester and a moving gas-holder. The gas holder floats either directly on the fermentation slurry or in a water jacket of its own. The gas is collected in the gas drum, which rises or moves down, according to the amount of gas stored. The gas drum is prevented from tilting by a guiding frame. If the drum floats in a water jacket, it cannot get stuck, even in substrate with high solid content.

## 3. Biomass for the production of biogas

In principle, all organic materials can ferment or be digested. However, only homogenous and liquid substrates can be considered for simple biogas plants. It is necessary to dilute the organic material (waste, wastewater, excrement etc.) with about the same quantity of liquid.

The maximum of gas-production from a given amount of raw material depends on the type of substrate. For instance cattle manure produces 200 $m^3$ methane/t ODM (ODM – Organic Dry matter) and 20 $m^3$ biogas/$m^3$ liquid; pig liquid manure produces 300 $m^3$ methane/t ODM and 30 $m^3$ biogas/$m^3$ liquid; sewage sludge produces 300 $m^3$ methane/t ODM and 5 $m^3$ biogas/$m^3$ sewage sludge; biowaste produces 250 $m^3$ methane/t ODM and 100 $m^3$ biogas/$m^3$ t; old fat produces 720 $m^3$ methane/t ODM and 650 $m^3$ biogas/$m^3$ t old fat (www.energymanager.eu/getresource/10018/biogas.pdf). This shows that when old fat is used as a substrate, the biogas yield is higher than that produced by cattle manure, pig manure, sewage sludge and biowaste. Heat retention time also varies with the type of substrate being used and the temperature in the digester. For liquid manure undergoing fermentation in the mesophilic temperature range (20–40 °C), the following approximate heat retention times apply:

liquid cow manure: 20–30 days,
liquid pig manure: 15–25 days,
liquid chicken manure: 20–40 days,
animal manure mixed with plant material: 50–80 days [14].

If the retention time is too short, the bacteria in the digester are "washed out" faster than they can reproduce, so that the fermentation practically comes to a standstill. This problem rarely occurs in agricultural biogas systems.

## 4. Biogas enrichment processes

Biogas enrichment processes are the methods of removing unwanted gases from biogas to increase its calorific value. The presence of incombustible gases like $CO_2$ and hydrogen sulphide $H_2S$ and water vapour reduce the calorific value of biogas and make it uneconomical to compress and transport to longer distances [11]. The removal of $CO_2$ and $H_2S$ increases the percentage of methane in the biogas thus enriching its content up to the natural gas level [22].

### 4.1. Methods for scrubbing carbon dioxide

The following are methods for removing carbon dioxide ($CO_2$) from biogas. Most of these methods are processes being used for removing $CO_2$ from natural gas in petrochemical industries. These may include physical or chemical absorption, adsorption on a solid surface, membrane separation, cryogenic separation and chemical conversion.

#### 4.1.1. Physical or chemical absorption (water scrubbing)

Physical/chemical absorption method is generally applied for biogas scrubbing as it is effective even at low flow rates that the biogas plants normally operate. Also the method is less complicated, requires fewer infrastructures and is cost effective. The cheapest method makes use of pressurised water as an absorbent.

When water scrubbing is used for $CO_2$ removal, biogas is pressurised, typically from 1.03 MPa to 2.07 MPa with a two-stage compressor [15], and then introduced into the bottom of a tall vertical column. The raw biogas is introduced at the bottom of the column and flows upward, while fresh water is introduced at the top of the column, flowing downward over a packed bed. The packed bed (typically a high-surface-area plastic media) allows for efficient contact between the water and gas phases in a countercurrent absorption regime. Water often pools at the bottom of the contact column and the biogas first passes through this water layer in the form of bubbles. The $CO_2$-saturated water is continuously withdrawn from the bottom of the column and the cleaned gas exits from the top.

A purity of about 95% methane can be readily achieved with minimal operator supervision in a single pass column. After scrubbing, the water can be regenerated (i.e., stripped of $CO_2$ by contacting with air at atmospheric pressures, either in a packed bed column similar to the one used for absorption, or in a passive system such as a stock pond).

Vijay et al. [22] designed a packed bed scrubber for 95% removal of carbon dioxide from biogas, thus reducing the percentage of carbon dioxide from 40% to 2% by volume in enriched biogas. The diameter of the scrubber and packed bed height was taken as 150 mm and 3500 mm respectively. The scrubber achieved 99% $CO_2$ absorption at a gas flow rate of 1.5 $m^3$/h and at 1.8 $m^3$/h water wash flow rate and at a gas pressure of 1.0 MPa. It was observed that the percentage of $CO_2$ increased as the gas pressure increased for all gas flow rates.

A Scrubbing unit was designed and developed by Ilyas [10]. The model was composed of a scrubbing unit which removed $CO_2$ by water scrubbing and the purified biogas was compressed and stored in cylinders. The scrubber was 150 mm in diameter and 4500 mm in height with 3500 mm in packed bed length. It was designed to purify the biogas from 60% to 95% methane by absorbing the 40% of $CO_2$ available in raw biogas to 5% in purified biogas thus increasing the methane level. Bhattacharya et al. [5] also developed a water scrubbing system, which achieved 100% pure methane but was dependent on factors like dimensions of scrubbing tower, gas pressure, composition of raw biogas, water flow rates and purity of water used.

A continuous counter-current type scrubber with gas flow rate of 1.8 $m^3$/h and at a pressure of 48 KPa and water inflow rate of 0.465 $m^3$/h was designed by Khapre [13]. It continuously reduced $CO_2$ from 30% at inlet to 2% at outlet by volume.

Dubey [7] experimented with three water scrubbers having diameters 150 mm (height: 1.5 m), 100 mm (height: 10 m) and 75 mm (height: 10 m) to absorb $CO_2$ present (37–41%) in the biogas. He found that the $CO_2$ absorption was influenced by the flow rates of gas and water rather than different diameters of scrubbers. Shyam [21] reported the 6 m high scrubbing tower developed by the G.B. Pant University of Agriculture and Technology, Pantnagar, India. It had a packed length of 2.5 m with spherical plastic balls of 25 mm diameter. The raw biogas compressed at 588 KPa pressure was passed at a flow rate of 2 $m^3$/h while water was circulating through the tower. A maximum of 87.6% of the $CO_2$ present could be removed from the raw biogas.

A water scrubbing system preceded by $H_2S$ removal would be a practical, low-cost process for upgrading dairy biogas to biomethane. It is important that the $H_2S$ be removed prior to the removal of the $CO_2$, as $H_2S$ is highly corrosive and would result in decreased life and higher maintenance of the subsequent compressors required in the CO-removal step.

#### 4.1.2. Chemical absorption

This method follows the principle of absorption of $CO_2$ gas using suitable bases to result an acid base neutralization reaction thereby, absorbing and reducing the $CO_2$ content in biogas [3]. Savery and Cruzon [20] suggested the use of NaOH, KOH and $Ca(OH)_2$ in the chemical scrubbing of biogas. The absorption of $CO_2$ in alkaline solution is assisted by agitation. The rate of absorption is also increased by the concentration of the solution. The rate of absorption is most rapid with NaOH at normality's of 2.5–3.0 [11].

#### 4.1.3. Adsorption on a solid surface

Adsorption process involves the transfer of solute in the gas stream to the surface of a solid material, where they concentrate mainly as a result of physical or Vander wall forces.

Commercial adsorbents are generally granular solids with a large surface area per metre squared. It is generally accomplished at high temperature and pressure and the silica, alumina, activated carbon or silicates, which are also known as molecular sieves, can be used as adsorbents. This method has good moisture removal capacities, simple in design and easy to operate. But it is a costly process with high pressure drops and high heat requirements [11].

#### 4.1.4. Membrane separation

This method works on the principle that some components of the raw gas could be transported through a thin membrane ($<1$ mm) while others are retained. This process uses pressure and a selective membrane, which allows preferential passage of one of the gases. The transportation of each component is driven by the difference in partial pressure over the membrane and is highly dependent on the permeability of the component in the membrane material [11].

For high methane purity, permeability must be high. An acetate–cellulose polymer membrane is useful for separating methane from $CO_2$ and $H_2S$ because it has a permeability up to 20 and 60 times, respectively, higher than $CH_4$ at a pressure of 2.5–4.0 MPa [9].

Rautenbach et al. [17] designed a pilot plant for the removal of $CO_2$ from biogas using the membrane separation technique. He reported that Monsanto and acetate cellulose membranes were more permeable to $CO_2$, $O_2$ and $H_2S$ than $CH_4$. The best separation occurred at 25 °C temperature and 5.5 KPa pressure. The gas flux across the membrane increases proportionally with the partial pressure difference. Thus, the higher the pressure difference, the smaller is the membrane area required.

#### 4.1.5. Cryogenic separation

Carbon dioxide $CO_2$, Methane $CH_4$, and contaminants all liquefy at very different temperature pressure domains, it is therefore possible to produce $CH_4$ from biogas by cooling and compressing the biogas to liquefy $CO_2$ which is then easily separated from the remaining gas. The extracted $CO_2$ also can be used as a solvent to remove impurities from the gas [15]. In a cryogenic method, crude biogas is compressed to approximately 80 bar. The compression is made in multiple stages with inter-cooling. The compressed gas is dried to avoid freezing during the cooling process. The biogas is cooled with chillers and heat exchangers top $-45$ °C, condensed $CO_2$ is removed in a separator. The $CO_2$ is processed further to recover dissolved methane, which is recycled to the gas inlet. This process brings about the recovery of pure component in the form of a liquid, which can then be transported conveniently and more than 97% pure methane is obtained [11].

#### 4.1.6. Chemical conversion method

Chemical conversion method produces an extremely high purity in the product gas. It reduces the undesirable gas concentrations to trace levels. Usually the chemical conversion process is used after bulk removal has been accomplished by other methods. An example is methanation, in which $CO_2$ and $H_2$ are catalytically converted to methane and water. However this process is extremely expensive and is not warranted in most biogas applications [8]. This process is also unsuitable because of the requirement of a large amount of pure hydrogen [11].

### 4.2. Methods for removing hydrogen sulphide

The concentration of $H_2S$ in biogas generated from animal manure typically ranges between 1000 and 2400 ppm, depending mainly on the sulphate content of the local water [15]. The presence of hydrogen sulphide in biogas varies with the feedstock and has to be removed in order to avoid corrosion in compressors, gas storage tanks and engines [25]. $H_2S$ is poisonous and corrosive as well as environmentally hazardous since it is converted to sulphur dioxide by combustion. It also contaminates the upgrading process. $H_2S$ can be removed either in the digester, from the crude biogas or in upgrading process [9].

The methods for removing hydrogen sulphide have been highlighted by Kapdi et al. [11]. They are as follows:

(1) Dry oxidation process and (2) liquid phase oxidation process.

#### 4.2.1. Dry oxidation process

It is a method for removing of $H_2S$ from gas streams by converting it either into sulphur or oxides of sulphur. This process is used where the sulphur content of gas is relatively low and high purities are required. Some of these methods are described below.

*4.2.1.1. Introduction of air/oxygen into the biogas system.* A small amount of oxygen (2–6%) is introduced in the biogas system by using an air pump. As a result, sulphide in the biogas is oxidised into sulphur and $H_2S$ concentration is thereby lowered.

$$2H_2S+O_2=2S+2H_2O$$

This method is simple and cost effective. No special chemicals or equipments are required.

Depending on the temperature, the reaction time and place where the air is added, the $H_2S$ concentration can be reduced by 95% to less than 50 ppm. However, care should be taken to avoid overdosing of air, as biogas in air is explosive in the range of 6–12%, depending on the methane content [25].

*4.2.1.2. Adsorption using iron oxide.* $H_2S$ reacts with iron hydrooxides or oxides to form iron sulphide. The biogas is passed through iron oxide pellets, to remove $H_2S$. When the pellets are completely covered with sulphur, these are removed from the tube for the regeneration of sulphur. It is a simple method but a lot of heat is released during regeneration. Also the dust packing contains a toxic component and the method is sensitive to high water content of biogas.

This method was used by Baron et al. [4], to scrub hydrogen sulphide. The $H_2S$ scrubbing mechanism was produced by using a glass bottle filled with steel wool to act as an $H_2S$ scrubber. The glass bottle was sealed with a metal screw-on top, which has two holes, one for an inlet tube, which reaches to the bottom of the bottle. The other hole was for an outlet tube, which reached just beyond the seal so that the gas moved through the length of the bottle before it passed out. Both holes were sealed with caulk. The biogas will pass through the setup before entering the compression system, and the pump will act as the driving force to move the gas through the steel wool.

Steel wool, however, has a relatively small surface area, which results in low binding capacity for the sulphide. Because of this, wood chips impregnated with iron oxide have been used as preferred reaction bed material. The iron-oxide impregnated chips have a larger surface-to volume ratio than steel wool and a lower surface-to-weight ratio due to the low density of wood.

Roughly 20 g of hydrogen sulphide can be bound per 100 g of iron-oxide impregnated chips [15]. Iron oxide or hydroxide can also be bound to the surface of pellets made from red mud (a waste product from aluminium production). These pellets have a higher surface-to-volume ratio than steel wool or impregnated wood chips, though their density is much higher than that of wood chips. At high $H_2S$ concentrations (1000–4000 ppm), 100 g of pellets can bind 50 g of sulphide. However, the pellets are more expensive than wood chips.

#### 4.2.2. Liquid phase oxidation process

This process is primarily used for the treatment of gases containing relatively low concentration of $H_2S$. It may be either (a) physical absorption process or (b) chemical absorption process.

In physical absorption process the $H_2S$ can be absorbed by the solvents. One of the solvents is water. But the consumption of water is very high for absorption of small amount of $H_2S$. If some chemicals like NaOH are added to water, the absorption process is enhanced. It forms sodium sulphide or sodium hydrosulphide, which is not regenerated and poses problems of disposal.

However in practice, the process is not regenerative and is thus prohibitively expensive. For this reason many choose to rely on water alone to absorb the $H_2S$. Vijay et al. [22] and Ilyas [10] designed a water tower to scrub $CO_2$, and absorb small amounts of hydrogen sulphide. Chemical absorption of $H_2S$ can take place with iron salt solutions like iron chloride. This method is extremely effective in reducing high $H_2S$ levels. The process is based on the formation of insoluble precipitates. $FeCl_3$ can be added directly to the digester slurry. This process is most suitable in small anaerobic digester systems. All other methods of $H_2S$ removal are suitable and economically viable for large-scale digesters. By this method the final removal of $H_2S$ is about 10 ppm.

In the final analysis, pre-removal of $H_2S$ (e.g., using iron sponge technology) is a more practical and environmentally friendly approach [15].

### 4.3. Elimination of water vapour

Biogas from digesters is normally collected from headspace above a liquid surface or very moist substrate, as a result of this, the gas is usually saturated with water vapour. The amount of saturated water vapour in a gas depends on temperature and pressure. Biogas typically contains 10% water vapour by volume at 43.33 °C, 5% by volume at 32.22 °C, and 1% by volume at 4.44 °C [23].

Various methods can be employed to eliminate this. A moisture trap may be constructed by placing a jar of water is placed outside the pit and a gas pipe of at least 20 cm long is put into it in downward projection. Any moisture condensing in the pipe flows into the jar instead of collecting in the pipe and obstructing the passage of gas. Water then overflows and is lost in the ground. The jar should always be full or the gas will escape (VITA, 1980). The simplest method to remove condensed water is to install horizontal pipe runs with a slope of 1:100. A drip trap or condensate drain can then be located at all low points in the piping to remove condensation. However, this will only remove water vapour that condenses in the piping [15].

Vijay et al. [22] used a set of three filters (Pre-filter, Micro-filter and Sub-Micro filter) in the Galvanised Iron pipeline connected with the storage pressure vessel (containing enriched biogas) and the three stage compressor. They were designed to remove almost all water vapour from the enriched biogas.

## 5. Compression and storage of enriched biogas

### 5.1. Compression of biogas

Biogas is compressed before storage because it reduces the storage requirements, concentrates energy content and increases pressure to the level required for overcoming resistance to gas flow [11]. Compression of scrubbed biogas is easier than compression of raw biogas. There are various kinds of compressors that can be used for compressing biogas and they all perform the same function, which is to increase the pressure and reduce the volume of the biogas. The most common type of compressor works by filling a chamber with air and then reducing the chamber's volume. These are called positive displacement compressors. They are the most widely available compressors and include reciprocating, rotary screw and rotary vane compressors. Of all the positive displacement compressors, reciprocating or piston compressors are the most commonly available on the market and can be found in ranges from fractional to very high horsepower.

Rotary compressors (Screw and Vane) and the centrifugal compressors are also commonly found but in more of an industrial/commercial environment. Normally they are operated at significantly higher horsepower and flow rates, which makes them more expensive buy and to operate (www.daveycompressor.com). Multi-stage air compressors work in a very similar manner with the primary difference being that they compress the air in two or more steps or stages. During the first step or stage, air is drawn in and compressed to an intermediate pressure. After being compressed in the first stage, the air is piped, usually through an intercooler where the air is allowed to cool, to be compressed in the final or second stage. Multi-stage compressors are normally good for pressures up to 200 psi. Multi-stage pumps are more efficient at higher pressures because the air is cooled between the stages. They are usually used to pump biogas for industrial applications (www.daveycompressor.com).

In compressing biogas, more than one compressor is usually used throughout the process. The reasons for this are stated below:

1. The biogas is usually compressed before it is scrubbed so that the gas enters the scrubber at a high pressure which enhances the absorption of carbon dioxide in the water tower.
2. The scrubbed biogas is also compressed to reduce storage requirements and to concentrate the energy content.

### 5.2. Storage of biogas

Biogas is usually produced in the farm where there is availability of feedstock (usually dairy manure). It is often necessary to store the biogas produced because most farms will produce more biogas than they can use on-site. It can be stored for later onsite usage or for transportation to off-site distribution points or systems.

Storage of biogas is very important because methane is a very combustible gas and the risk of storage at high pressure is also high. Biogas must be stored in vessels that are compatible with the pressure of the gas. Most commonly used biogas storage systems can be seen in Table 1.

#### 5.2.1. Low pressure storage of biogas

Floating gas holders on the digester form a low-pressure storage option for biogas systems.

These systems typically operate at pressures up to 10-in. water column (less than 13.79 KPa).

**Table 1**
Commonly used storage options for biogas.
*Source*: Kapdi et al. [11].

| Pressure | Storage device | Material |
|---|---|---|
| Low (0.138–0.414 bar) | Water sealed gas holder | Steel |
| Low | Gas bag | Rubber, plastic, vinyl |
| Medium (1.05–1.97 bar) | Propane or butane tanks | Steel |
| High (200 bar) | Commercial gas cylinders | Alloy |

Floating gas holders can be made of steel, fibre glass, or a flexible fabric [15]. The least expensive and most trouble-free gas holder is the flexible inflatable fabric top, as it does not react with the H2S in the biogas and is integral to the digester.

*5.2.2. Medium-pressure storage of cleaned biogas*

Biogas can also be stored at medium pressure between 13.79 and 1378.96 KPa. It is however necessary to first clean the biogas to remove $H_2S$ in order to prevent corrosion of the tank components and to ensure safe operation (). Typical propane gas tanks are rated to 1723.7 KPa. Compressing biogas to this pressure range uses about 5 kWh per 1000 $ft^3$ [26]. Approximately 10% of the energy content of the stored biogas is usually needed for compression of biogas [26].

*5.2.3. High-pressure storage of biogas*

There is the need to enrich/clean biogas before it can be stored at high pressure. Enriched biogas is often called biomethane and has a higher calorific value than biogas and can be stored as compressed BioMethane (CBM) to save space. Gas scrubbing is even more important at high pressures because impurities such as $H_2S$ and water are very likely to condense and cause corrosion. The gas is stored in steel cylinders such as those typically used for storage of other commercial gases. Storage facilities must be adequately fitted with safety devices such as rupture disks and pressure relief valves. The cost of compressing gas to high pressures between 13.79 MPa and 34.47 MPa is much greater than the cost of compressing gas for medium-pressure storage.

Compression to 13.79 MPa requires nearly 14 kWh per 1000 ft of biomethane [26]. If the biogas is upgraded to 97% methane and the assumed heat rate is 12,000 Btu/kWh, the energy needed for compression amounts to 17% of the energy content of the gas.

Vijay et al. [22] used a low suction capacity and high pressure three stage compressor to compress the enriched biogas to a pressure of 20 MPa. The compressed biogas was stored in high pressure steel cylinders that are readily available in the market for CNG storage. The biogas was tested on a vehicle (Maruti-800 car). The test results on performance were observed as good as on CNG operated Maruti-800 car in terms of easy and quickstarting and smooth running after engine tuning and restriction in air intake. Ilyas [10] also used a three-stage compressor to compress purified gas up to $20 \times 10^3$ KPa pressure and it was stored in 0.0215 $m^3$ water capacities CNG cylinders. However, Baron et al. [4] designed and constructed a manually operated reciprocating piston compressor for compressing purified biogas to compress the biogas to approximately 241.3 KPa in a 7 gallon air tank. The pump includes three cylinders that are supported to stand vertically by a simple A-frame, based on an "inclined foot pump" design. The pump has an A-frame which helps the cylinder remain upright, and a long lever arm with which the operator pumps using the hands. The compressed gas was thereafter stored in an air tank fitted with a blow-off valve which preserves the pressure of the tank at 965.25 KPa.

## 6. Ecological and economic advantages of biogas in Nigeria

The production of biomass especially from the farmyard in livestock production systems is an ecological component that is cleaned up and utilised to the advantage of a community in the concept of biogas production. It has been classified as a clean energy source in the sense that it does not come with the environmental pollution and degradation that comes with the petrochemical industries as a source of energy production. The latter contributes to the depletion of the ozone layer with the resultant climate change and earth surface (life) discomfort. Clean energy from biogas has another advantage in being highly renewable in that it comes readily with agriculture, itself a source of food for human existence. Therefore, in essence, biogas is a high yielding economic potential for Nigeria in being a means of recirculation of farm waste obtained from feeding over 150 million people and at the same time, cleaning up the farmyard and generating energy for powering the industrial and domestic bases of the country. Essentially, every household has the potential of tapping into this energy production chain that is capable of meeting local needs and promoting ecosystem health. There are potential sources of substrate for biogas plants in Nigeria. For instance, Nigeria generates about 4.075 million Tonnes of municipal waste, 11.244 million tonnes of agro-waste which has an energy value of 147,700 MJ, 1.8 million tonnes of Saw dust with an energy value of 31,433 MJ [19] all these are sources of substrate for a large scale biogas plant which has the potential of contributing immensely to the generation of electricity, especially the rural areas in Nigeria.

## 7. Energy production from biogas

Biogas has a lot of applications for both on-farm and off-farm purposes. Raw biogas has a low energy density of only about 22.3 $MJ/m^3$ and it is also highly corrosive in nature (due to the presence of $H_2S$ and water). This reduces the potential for off-farm use greatly [15]. The most common and popular on-farm use of biogas is to fuel an engine-generator to produce electricity for on-farm use. It is suitable for Combined Heat and Power (CHP) applications such as powering boilers and burners. The biogas could also be used as fuel for irrigation pumps and engine driven refrigeration compressors.

Enriched Biogas however, has a heat capacity of about 36.2 $MJ/m^3$. Because of this high energy content, it could be sold for off-farm applications to industrial or commercial users, for injection into a natural gas pipeline, or as vehicular fuel. Petrol engines can be converted to burn treated biogas by

(1) modifying carburetion to accommodate the lower volumetric heating value of the biogas (14.98–22.47 $MJ/m^3$) compared to natural gas (37.45 $MJ/m^3$) and
(2) adjusting the timing on the spark to accommodate the slower flame velocity of biogas ignition systems.

Gas treatment to prevent corrosion from $H_2S$ is usually not necessary if care is taken with engine selection and proper maintenance procedures are followed. Typically, oil changes are recommended every 600 h for a natural gas engine. When operating on raw biogas, oil changes should be conducted every 300 h [15]. Diesel engines can also be modified to operate on biogas in two ways: (1) by replacing the fuel injectors with spark plugs and replacing the fuel pump with a gas carburetor, and (2) by using diesel fuel for ignition and adding a carburetor for the biogas as well as advancing the ignition timing. The high compression ratio of a diesel engine (16:1) lends itself to operation on biogas. Spark-ignited gas engines tend to operate in the lower 7:1 to 11:1 range of compression ratios, whereas biogas engines ideally operate in the 11:1–16:1 range [15].

For CHP applications, the key to energy savings is recovering heat generated by the engine jacket and exhaust gas. Exhaust temperatures can reach as high as 648.89 °F. In order to recover this heat from biogas engines, jacket-water and exhaust-gas heat-exchange devices must be used.

Heat recovery from exhaust is carried out through a gas-to-liquid heat exchanger. The heat recovery system should maintain

temperatures no lower than 204.44 °F to prevent acidic vapours from condensing and corroding the exhaust-heat recovery package.

Enriched biogas is more versatile compared to raw biogas. It has more potential for commercialisation and will be more valuable if enriched and bottled.

## 8. Current advances in biogas enrichment, compression and storage

In Vijay et al. [22] and Ilyas [10] it was observed that the $CO_2$ removal using a water scrubber achieved 95% $CO_2$ absorption, meaning the percentage of methane in the biogas could still be increased by absorbing more $CO_2$. It will therefore be necessary to incorporate a multistage scrubber in the design so that the second stage scrubber acts on the first stage purification and gives a purer biogas (Project ongoing). Water scrubbing removes some amount of hydrogen sulphide $H_2S$, however, it is at a low rate of absorption. Water scrubbing of $H_2S$ results in the production of fugitive $H_2S$ emissions. It is therefore necessary to remove hydrogen sulphide by another method before scrubbing the biogas. The authors are exploring the removal of hydrogen sulphide using the mixture of steel wool and wood chips prior to water scrubbing for the removal of $CO_2$.

Cattle manure is widely used in the production of biogas in most plants. However, there are other substrates which have a higher methane yield than cattle for instance, pig liquid manure, Poultry manure, sewage sludge, old fat, cut grass etc. [7]. The authors are exploring the possibility of mixing substrates for higher biogas yield. New options such as Cheese whey [12] and freshwater algae [6] are also being explored.

## 9. Conclusion

Biogas being a renewable energy that is commonly available in both rural and urban communities is considered a viable solution to the energy challenges of Nigeria. In view of the long and continuing exploration of crude oil in the Niger delta of Nigeria and its attendant pollution of the environment, a clean and renewable energy source will provide a paradigm shift that is needed for a more stable and evenly distributed economy.

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